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Abstract

Having reliable estimates of the number of water bodies on different geographical scales is of great importance to better understand biogeochemical cycles and to tackle the social issues related to the economic and cultural use of water bodies. However, limnological research suffers from a lack of reliable inventories; the available scientific references are predominately based on water bodies of natural origin, large in size and preferentially located in previously glaciated areas. Artificial, small and randomly distributed water bodies, especially ponds, are usually not inventoried. Following Wetzel's theory (1990), some authors included them in global inventories by using remote sensing or mathematical extrapolation, but fieldwork on the ground has been done on a very limited amount of territory. These studies have resulted in an explosive increase in the estimated number of water bodies, going from 8.44 million lakes (Meybeck 1995) to 3.5 billion water bodies (Downing 2010). These numbers raise several questions, especially about the methodology used for counting small-sized water bodies and the methodological treatment of spatial variables. In this study, we use inventories of water bodies for Sweden, Finland, Estonia and France to show incoherencies generated by the "global to local" approach. We demonstrate that one universal relationship does not suffice for generating the regional or global inventories of water bodies because local conditions vary greatly from one region to another and cannot be offset adequately by each other. The current paradigm for global estimates of water bodies in limnology, which is based on one representative model applied to different territories, does not produce sufficiently exact global inventories. The step-wise progression from the local to the global scale requires the development of many regional equations based on fieldwork; a specific equation that adequately reflects the actual relationship between distribution and abundance of water bodies in a given area must be produced for each geographical region.

Zusammenfassung

Verlässliche Schätzungen über die Zahl der Gewässer auf verschiedenen räumlichen Ebenen sind von großer Bedeutung, um biogeochemische Kreisläufe besser zu verstehen und um die Fragen im Zusammenhang mit der

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wirtschaftlichen und sonstigen gesellschaftlichen Nutzung von Gewässern anzugehen. Dabei besteht jedoch in der limnologischen Forschung ein Mangel an zuverlässigen Inventaren der Wasserflächen; die verfügbaren wissenschaftlichen Quellen basieren überwiegend auf Übersichten eher größerer Gewässer und solcher natürlichen Ursprungs, zudem bevorzugt in ehemals vergletscherten Gebieten. Künstliche, kleine und unregelmäßig verteilte Wasserflächen, vor allem Teiche, werden in der Regel nicht inventarisiert. Unter Verwendung der *Wetzel*'schen Theorie (1990) nahmen einige Autoren sie in globale Bestandsverzeichnisse mit auf, in dem sie Fernerkundung oder mathematische Extrapolation zum Einsatz brachten, Erhebungen im Gelände sind dagegen nur für eine sehr begrenzte Zahl von Gebieten durchgeführt worden. Diese Studien haben zu einer explosionsartig starken Zunahme der geschätzten Anzahl von Wasserflächen geführt, und zwar von 8,44 Mill. Seen (*Meybeck* 1995) auf 3,5 Mrd. Gewässer (*Downing* 2010). Diese Zahlen werfen mehrere Fragen auf, insbesondere zur Methodik beim Zählen kleinräumiger Gewässer und zur Behandlung verschiedener räumlicher Variablen in diesem Prozess. In dieser Studie verwenden wir Bestandsübersichten von Wasserflächen in Schweden, Finnland, Estland und Frankreich, um Unstimmigkeiten aufzuzeigen, die beim Ansatz „vom Globalen zum Lokalen" entstehen. Wir zeigen, dass eine universell gültige Beziehung nicht ausreicht zur Erstellung regionaler oder globaler Bestandsübersichten der Wasserflächen, da die örtlichen Gegebenheiten stark von einer Region zur anderen variieren und diese Unterschiede auch nicht gegeneinander aufgerechnet werden können. Die gegenwärtig übliche Methode globaler Schätzungen der Zahl der Gewässer in der Limnologie, die auf einem repräsentativen Modell basiert, das auf verschiedene Gebiete angewendet wird, liefert keine hinreichend genauen globalen Inventare. Deshalb sollte im Gegensatz dazu schrittweise vorgegangen werden, von der lokalen zur globalen Ebene, was die Erstellung vieler regionaler Gleichungen erfordert, auf der Grundlage von Geländearbeit; für jede Region muss eine spezifische Gleichung aufgestellt werden, die die tatsächliche Beziehung zwischen der Verteilung und der Größe der Wasserflächen in dem gegebenen Gebiet widerspiegelt.

Keywords Inventory, lake, pond, scale, bodies of water

1. Introduction

A knowledge of the number and area of terrestrial standing bodies of water on different scales is of great importance in better understanding biogeochemical cycles (*Cole* et al. 2007, *Verpoorter* et al. 2014) as well as in tackling the social issues related to the economic and cultural use of ~~bodies of water.~~ As *Downing* et al. state, "one of the major impediments to the integration of lentic ecosystems into global environmental analyses has been fragmentary data on the extent and size distribution of lakes, ponds and impoundments" (*Downing* et al. 2006: 1). Questions about carbon burial, water quality, eutrophication, water balance and thermal balance require a detailed inventory of lakes, reservoirs and ponds (farm, urban, dew and leisure purposes) (*Duck* 2012), as much as of their economic (hydropower, fishing), cultural (for example rural heritage) and management functions. In order to provide quantitative estimates on regional and local levels, scientists need to develop and apply reliable estimates of the total number of all bodies of water in the world.

In addition, in the European Union, knowledge concerning the distribution and abundance of water bodies is a management necessity for the realization of measures for improving "water masses/water bodies" characteristics as defined by the European Water Framework Directive (2000).

Currently, estimates of the number of water bodies for scientific and administrative purposes are based on bodies of water of natural origin (lakes) or large in size (lakes and reservoirs) and preferentially located in previously glaciated areas. Artificial, small and randomly distributed bodies of water are usually not inventoried even by local administrative units. Only a few databases also take small bodies of water into account. For example, the inventories presented by *Kuusisto* and *Raatikainen* (1988) and *Kuusisto* (2012) include small natural lakes of down to 0.05 ha; and *Bartout* and *Touchart* (2013) have inventoried artificial ~~bodies of water~~ of as small as 0.01 ha. Overall, the reliable determination of a global inventory of terrestrial standing bodies of water remains a difficult task.

Since the first study carried out by *Halbfass* (1933), classical global counting of ~~bodies of water~~ has estimated a total number and area of natural bodies of water above some thresholds: 13,543 (*Meybeck* 1995) to 17,357 lakes (*Lehner* and *Döll* 2004) above 10 km², 1.24 million (*Meybeck* 1995) to 1.86 million lakes

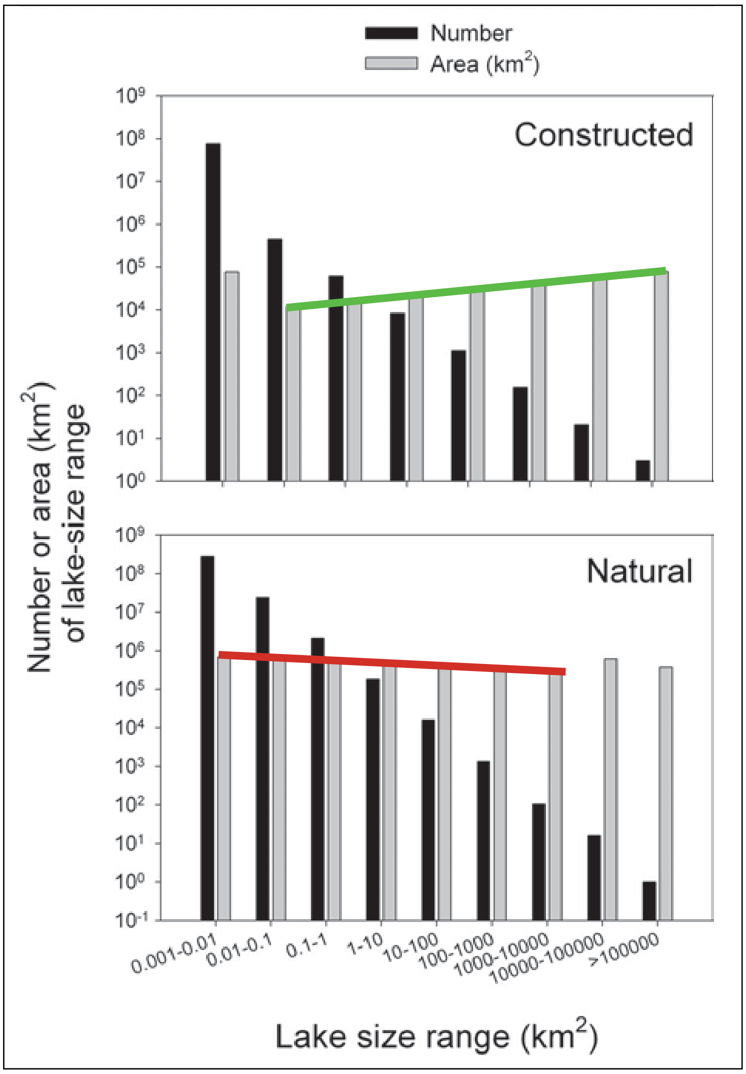

Fig. 1 Global size distribution of numbers and land area covered by natural and man-made lakes. Source: Downing 2010, with the trend lines added (in colour)

(*Tamrazyan* 1974) above 10 ha, 6.65 million (*Rjanžin* 2005) to 8.44 million lakes (*Meybeck* 1995) above 1 ha. Estimates of the global lake area range from 1.525 million km^2 (*Nace* 1969) to 2.0587 million km^2 (*Shiklomanov* 1993), 2.428 million km^2 (*Lehner* and *Döll* 2004), 2.5 million km^2 (*Thienemann* 1925), 2.69 million km^2 (*Rjanžin* 2005) and 2.7 million km^2 (*Tamrazyan* 1974, *Meybeck* 1995).

Because of the multitude, it is not possible to count all bodies of water in the field. Several authors (*Downing* et al. 2006, *Minns* et al. 2008, *Downing* and *Duarte* 2009, *Downing* 2010, *Oertli* and *Frossard* 2013) have attempted to provide an approximate estimate of total numbers by using mathematical models. They have suggested a correlation between the number of lakes and the area for each of four or five size categories (0.1-1, 1-10, 10-100, 100-1,000, above 1,000 km^2). The main idea is based on a general trend, according to which, for each class, the total area decreases with the decreasing size of the lakes (*Fig. 1*).

This theory originates from work by *Wetzel* (1990). *Wetzel's* theory presupposed that there is a correlation between area (and depth[1]) and number of water bodies. *Wetzel* recognized that current inventories and the growing number of little stagnant bodies of water were inaccurate, and in order to quantify potential lakes and lake areas, he proposed the following approach: "Examination of the quantity of lakes versus lake area can only be done reasonably on a log-log plot because of the numbers involved" (*Wetzel* 1990: 10).

However, it is important to note that *Wetzel's* conclusions were based on his fieldwork on natural lakes in the high latitudes of the Northern hemisphere. However, globally there are many types of water bodies, such as large or small, deep or shallow, natural or artificial. Their origins and distribution vary depending on geology, climate, water balance, situation of groundwater, topography, altitude, economic trends, sociology, historical conditions and so on. Such factors have so far been omitted in works on inventories of ~~bodies of water~~ on a global scale, based on mathematical extrapolations (*Downing* et al. 2006, *Hakanson* and *Peters* 1995, *Meybeck* 1995) as well as remote sensing (*McDonald* et al. 2012, *Seekell* et al. 2013, *Verpoorter* et al. 2014).

Since 2006, an epistemological rupture has happened with the studies carried out by *J.A. Downing* and his collaborators. A new approach to the estimates of a global lake count showed three major differences:

First, the global trend concerning area has changed: the total area of lakes increases with the decreasing size of the lakes. Consequently, extending this trend to very small lakes (0.001-0.1 km^2), the total number of lakes presents an explosive increase, up to 303.8 million lakes that would cover 4.2 million km^2 (*Downing* et al. 2006).

Secondly, artificial bodies of water (above 0.01 km^2) are taken into account on a global scale. For this kind of water body, the original trend of total area decreasing with the decreasing size of water bodies remains unchanged (*Fig. 1*). As a result 515,149 reservoirs are counted for a total area of 258,570 km^2. In the same paper, this demonstration is extended to impound-

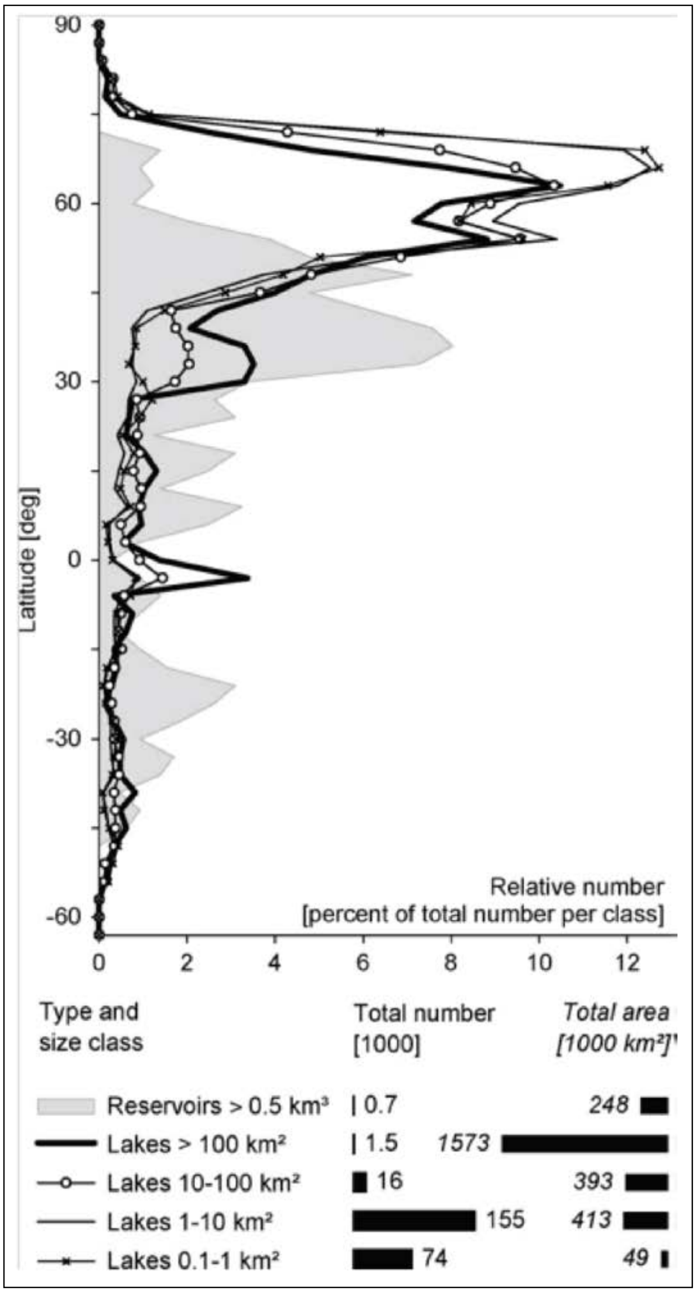

Fig. 2 Latitudinal distribution of global lake and reservoir numbers for different size classes. Source: Lehner and Döll 2004

ments, but only their total area is given (76,830 km^2). In 2009, a new estimate appears: 77.345 million impoundments (*Downing* and *Duarte* 2009). This number provides a cumulative extension of ponds above 0.1 ha, but the methodology has changed: artificial ponds are treated as small natural lakes (*Fig. 1*).

Thirdly, in 2010, the sum of natural and artificial bodies of water and an additional class (0.0001 to 0.001 km^2) were proposed, so that millions became billions. According to *Downing* (2010) there are 3.5 billion of ~~bodies of water~~ above 0.01 ha, and according to *Oertli* and *Frossard* (2013) 3.3 billions.

This explosive increase in water body numbers raises several questions, especially about the methodology for counting small-size bodies of water and the methodological consideration of spatial variables (climate, precipitation and hydrobelts, as in *Meybeck* et al. 2012). For example, would it be possible to obtain realistic inventories without the drudgery of fieldwork or post-processing, especially for the smallest bodies of water?

The main aim of this article is to determine whether the quantities of lentic bodies and the typology of water bodies influence their inventory. In order to do so, in this study, we (1) check the validity or invalidity of the extrapolations from models by *Meybeck* and *Downing*, (2) establish new correlations for small artificial bodies of water, and (3) take into account different geographical scales and regions.

To demonstrate these steps, we will use lake estimates on the European Union scale which represents a territory with a geographically diverse distribution of bodies of water (*Lehner* and *Döll* 2004; *Fig. 2*) and which is governed by a legislation that requires the collection of data concerning regional water body estimates (Water Framework Directive 2000).

Lehner and *Döll* have shown (*Fig. 2*) that, globally, the maximum number of reservoirs and artificial bodies is located in the middle latitudes and the maximum number of natural lakes is situated in the high latitudes. After all, the European Union territory covers both types of maxima for bodies of water; their spatial distribution (*Fig. 3*) was mapped in a database developed by *Bartout* (2015).

Using OpenStreetMap data processing, this location map of water bodies (*Fig. 3*) shows some geographic ruptures in the location of water bodies occurring where previously glaciated and non-glaciated regions meet, particularly visible from North Germany to South Lithuania.

Nonetheless, although this database has a better accuracy than all the official databases in the European Union, its suitability poses questions (*Bartout* 2015). Therefore, in this study, we improve the lake count by using local inventories from four countries: France, Estonia, Finland and Sweden. Using inventories from these countries located in different geographical areas, we compare two different ways of extrapolating the lake counts – the Swedish model (*Hakanson* and *Peters* 1995) and the

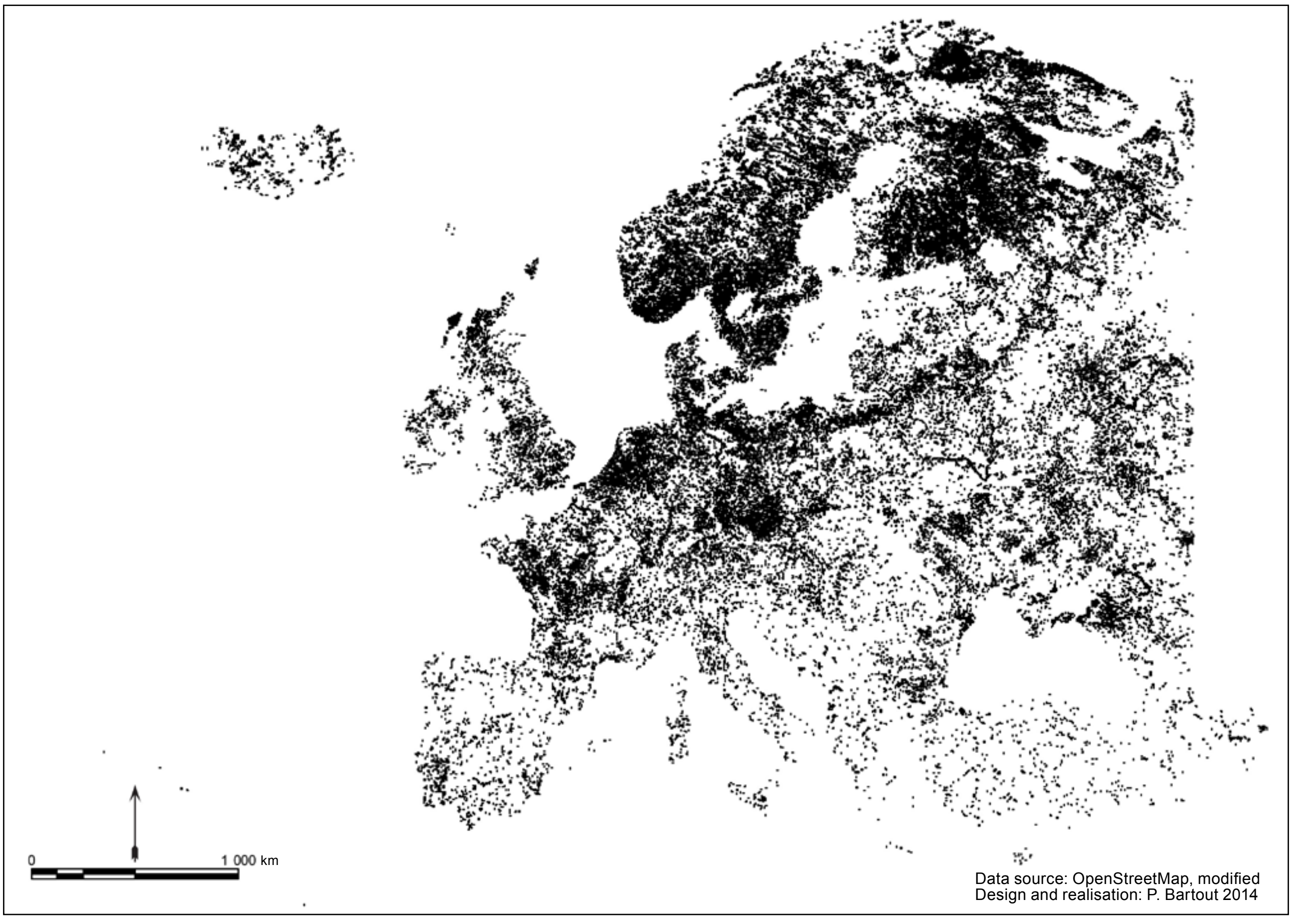

Fig. 3 Bodies of water in the whole territory of the European Union (after processing of OpenStreetMap data; Bartout 2015)

French model (*Bartout* and *Touchart* 2013). We evaluate their usefulness by comparative tests with databases of water bodies that have good lake counts records from fieldwork on the ground (Finland, Estonia).

2. Methodology

This study combines datasets from four EU countries (France, Sweden, Finland and Estonia) with different limnological features and with different methods of data collection and estimates for applying theoretical formulae to the counts checked on the ground and, conversely, for applying new formulae (from counts checked on the ground) to other countries.

2.1 Site description

Furthermore, in three cases (France, Estonia and Finland) it is possible to compare between equations based on checked counts in different geographical regions. The three states were chosen because of the availability of reliable inventories and the location of real bodies of water (*Fig. 4*).

Sweden (449,965 km^2), Finland (338,145 km^2) and Estonia (45,215 km^2) belong to the boreal region of Europe. The surface topography is flat (60 % of the territory is lower than 50 m a.s.l. in Estonia, as are the Ostrobothnia plains in Finland), except for some margins (Savonia, Northern Karelia, Kainuu and Lapland in Finland, the Scandinavian Mountains in Sweden). The majority of lake basins were formed during the ice retreat after the Last Glacial Maximum. Besides forests (50 % in Estonia, 68 % in Finland, 70 % in Sweden), wetlands are the most common landscape feature covering 20 % of the territory. Peat-rich mires with characteristic bog pools are abundant. Creation of man-made lakes and ponds has been relatively common throughout the centuries; these kinds of water bodies serve a range of ecological, cultural and agricultural purposes.

The territory of France (547 030 km^2) possesses a wide variety of coastal, lowland and mountain land-

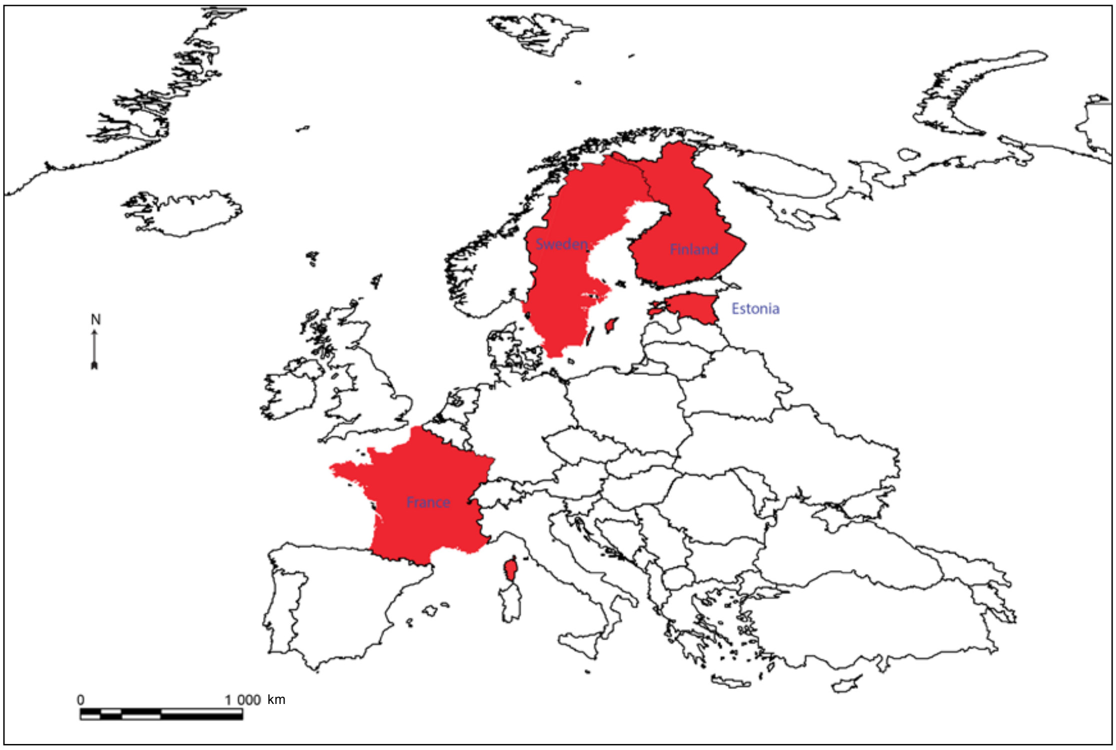

Fig. 4 Countries studied and their locations in Europe

scapes. Forests account for 28 % of the land area. The territory has extensive river systems, with Seine, Loire, Garonne and Rhône as the largest. Most of the bodies of water are artificial (~ 98 %), smaller than Nordic lakes and built on fluvial continuum.

2.2 Data sources

On the European Union scale, the most advanced mathematical extrapolations of counts of water bodies have been developed for Sweden. The country has been used as a test area in previous studies of lake counts (*Hakanson* and *Peters* 1995, *Verpoorter* et al. 2014), therefore we will also use a database of Swedish lakes for demonstration tests in cases when field checks for the smallest bodies of water have not been realized (*Table 1*).

Table 1 Water body inventory by size range in Sweden (Source: Hakanson and Peters 1995)

Size range (km²)	Number of water bodies
More than 1,000	3
100 to 1,000	19
10 to 100	362
1 to 10	3,987
0.1 to 1	19,374
0.01 to 0.1	59,500
0.001 to 0.01	144,000
0.0001 to 0.001	293,000
Total	520,245

Finland and Estonia represent countries where exhaustive inventories based on extensive field measures and topographic map analyses, without mathematical extrapolation, have been realized.

In Finland, the pioneers for counting all sizes of lake are *Kuusisto* and *Raatikainen* (1988). In Estonia, the recent limnic inventories (Estonian Lakes Inventory 2006, Estonian Topographic Database 2014) provide information not only on lakes but also bodies of water in general. The database was constructed from aerophotos and then checked on the ground.

The last inventory is from France, which has limnological features which differ from the previous regions. With the exception of a few mountain margins, France was not glaciated during the Würm period. However, the territory has numerous artificial bodies of water (ponds). In a similar way to the Estonian database, *Bartout* and *Touchart* (2013) provide a database of lakes based on aerophotos (database "Topo IGN" with aero-

Table 2 Water body inventories by size range in Finland (Kuusisto and Raatikainen 1988), Estonia (Estonian Topographic Database 2014) and France (Bartout and Touchart 2013)

Size range (km^2)	Number of water bodies		
	Finland	Estonia	France
More than 1,000	3	1	0
100 to 1,000	44	2	2
10 to 100	279	0	23
1 to 10	2,283	49	268
0.1 to 1	13,094	348	3,678
0.01 to 0.1	40,309	1,999	46,140
0.001 to 0.01		12,831	201,549
0.0005 to 0.01	131,876		
0.0001 to 0.001		71,273	302,684
TOTAL	187,888	86,503	554,344

photos from 2001-2005), supported by a ground check for 15,000 bodies of water of all sizes and all ages.

The essential figures of these inventories are assembled in *Table 2*.

2.3 Different models to inventory bodies of water

The Swedish model: *Meybeck* (1995) collected the number of lakes per area around the world. Lake density defined as number per million km^2 of each size category is an important characteristic of the global distribution of water bodies. It increases by a factor of 10 when the size of water bodies considered decreases. *Hakanson* and *Peters* (1995) applied the same relationship to Sweden and extended the extrapolation to very small lakes (less than 10 ha). A negative linear regression was elaborated: $y = -3.834*x + 6.147$ with a determining coefficient of 0.999.

In the EU, we can test this model by application to two types of territories: Nordic countries and countries located in the middle latitudes.

We apply this modeled relationship to the fennoscandian countries of Finland and Estonia in order to answer the following questions: does the total number of water bodies correspond to the real situation? Are size ranges in accordance with results of a log-log plot? Accordingly so, may the Swedish model be the Nordic model, implying “land previously glaciated and occupied by natural lakes”? May this “model” be expanded to other territories? Will the log-log method be successful to adequately estimate number of bodies of water in France?

The French model: The third question of this study aims to understand a reversed relationship between modeled estimates and ground reality: instead of an international limnic model based on a Nordic model, we want to apply the size ranges that fit the lake distribution in France to estimate the number of ~~bodies of water~~ in Nordic states.

3. Results

The application of size ranges from the Swedish model for all bodies of water below 10 ha to the database from Finland and Estonia produces two very different results. In Finland this application causes a doubling (+ 187 %) of the number of water bodies. This phenomenon becomes more pronounced with a decrease in the size of bodies of water (*Fig. 5*).

However, when applied to Estonia, the modeling results are completely different. In contrast to Finland, where the model overestimates the total lake count, in Estonia the number of lakes is underestimated (compared to the Estonian Topographic Database 2014). Indeed, the first inventory (Estonian Lakes Inventory 2006), which similarly to the Swedish model, primarily inventories natural “lakes”, underestimates small bodies of water due

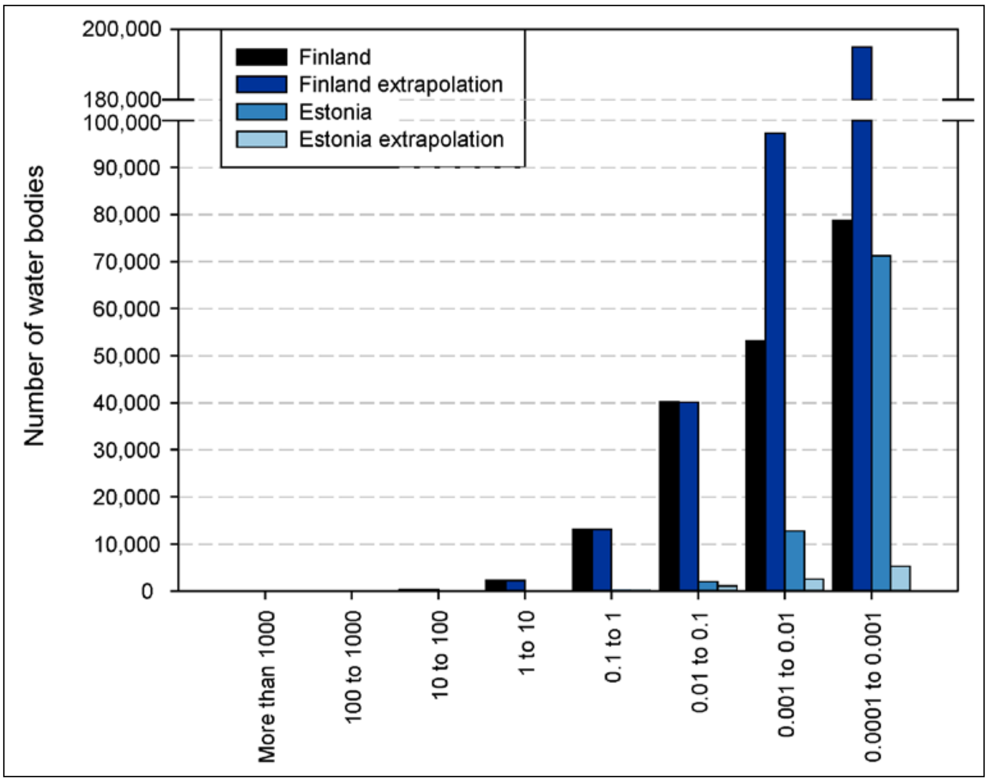

Fig. 5 Number of bodies of water in Finland and Estonia as estimated using the Swedish model

to the lack of extrapolation: there were 2,306 bodies of water over 1 ha in 2006 and 2,399 in 2014, an increase of 4 %, but there were 498 bodies of water under 1 ha in 2006 and 84,004 in 2014, an increase of 16,000 %!

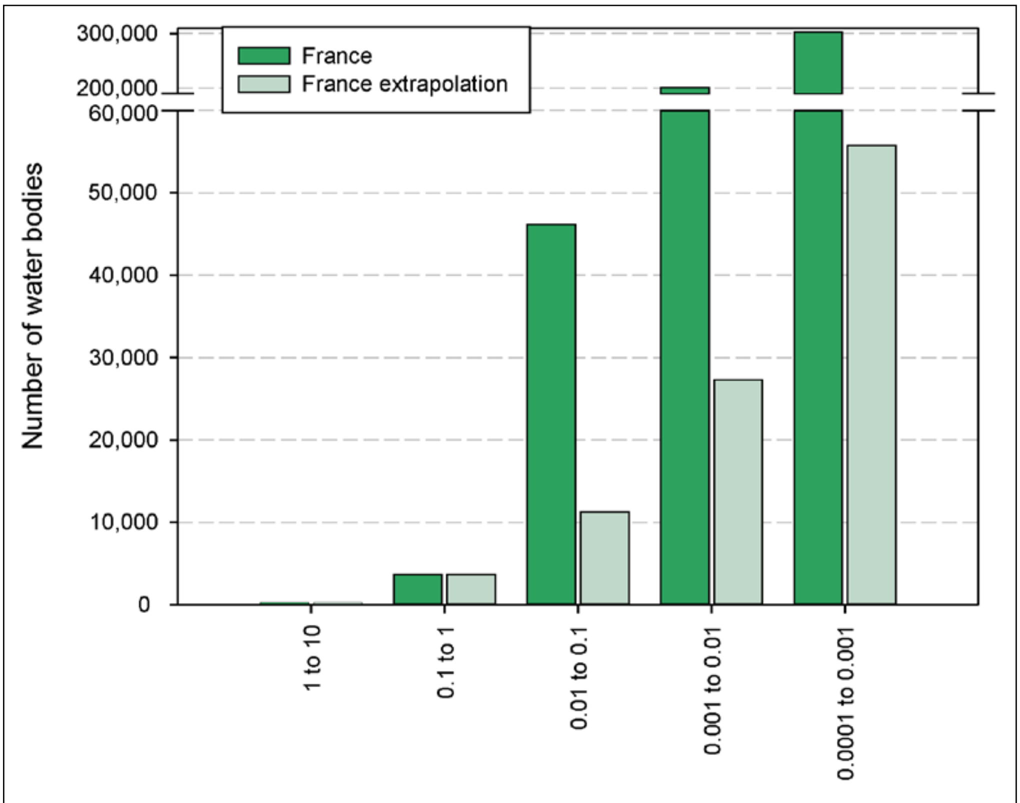

Fig. 6 Number of bodies of water in France as estimated by the Swedish model

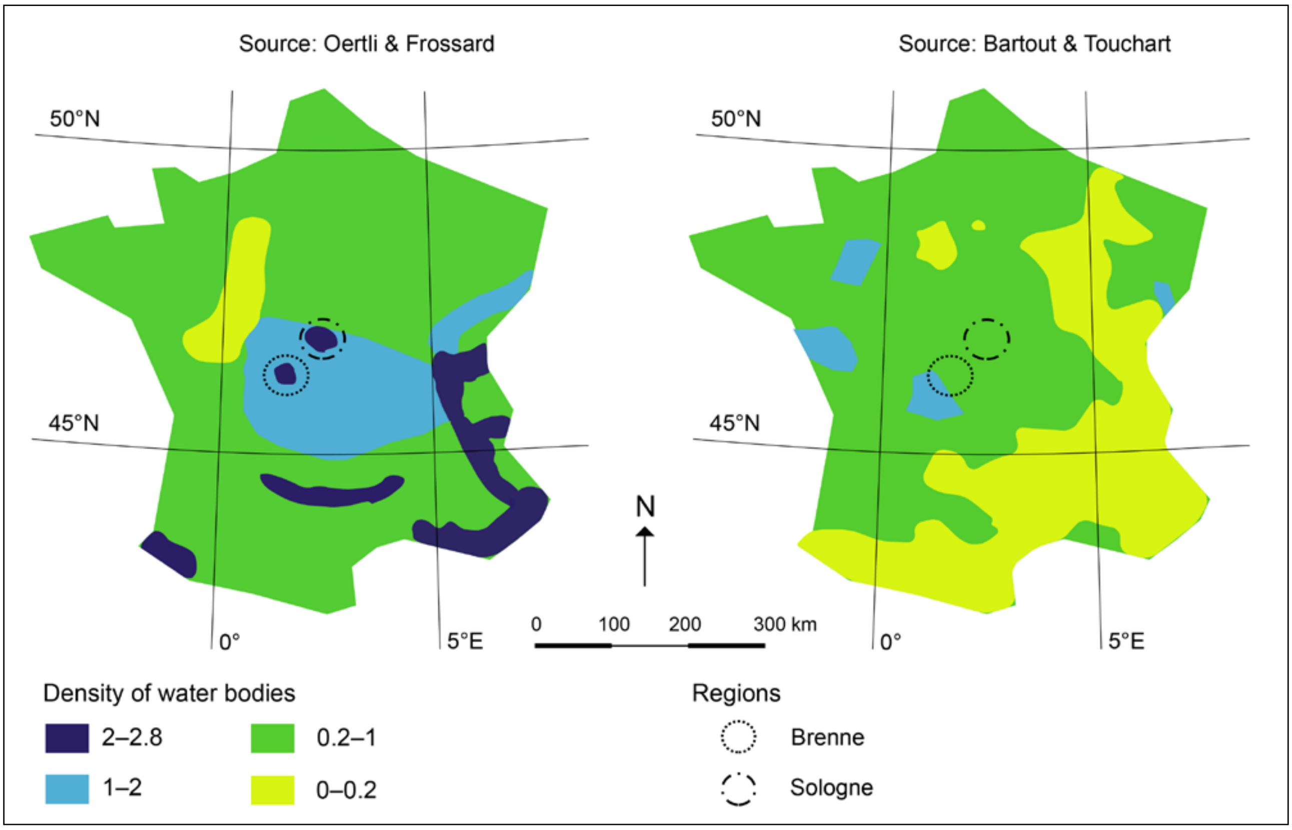

Fig. 7 Schematic comparison of densities of small bodies of water (between 1,000 m² and 1 ha) in France. The map on the left represents the theoretical estimates (Oertli and Frossard 2013) and the map on the right represents reality (Bartout and Touchart 2013). Design: P. Bartout, Q. Choffel and J. Saudubray; realisation: Q. Choffel, J. Terasmaa and A. Marzecova. Sources: Map interpretation from Oertli and Frossard 2013, BD Topo changed by P. Bartout

The total number of lakes in Estonia obtained by using the Swedish model equals barely more than 10 % of limnic reality. The gap between modeled and observed lake count increases with the decreasing size of water bodies: 50 % of reliability for the 0.01 to 0.1 km² size range, 20 % of reliability for the 0.001 to 0.01 km² range and 7 % for the last (0.0001 to 0.001 km²).

Moreover, because of the fact that the Finnish inventory used quality (bodies of water below a size less than 0.0005 km² are not inventoried), all Finnish results imply a significant underestimation of the distribution and number of ponds. This is particularly likely if we assume that the distribution of small bodies of water in Finland is similar to their distribution in Estonia where 97 % of the total number of water bodies is in the "under 1 ha" size class. If the distribution of bodies of water across size classes in Finland is comparable to Estonia, the estimated number of water bodies in Finland is 1.8 million. Taking this into consideration, we can assume that the Swedish model underestimates the count of Finnish water bodies.

Similarly, when applied to France (*Fig. 6*), the Nordic modeling tremendously underestimates the total count of bodies of water. The total number estimated by the model is less than 100,000 bodies of water whereas in reality the total number of bodies of water in France exceeds 550,000 (17.7 % reliability). However, there are some differences in the modeled results among the studied countries. For example, in contrast with Estonia, the largest gap between modeled and observed lake count (13.6 % of reliability) occurs in the 0.001 to 0.01 km² class level, and then the gap decreases with decreasing lake size (18.4 % reliability).

Whereas this demonstration shows high numerical differences between inventories built by mathematical extrapolation and the reality checked by fieldwork in Nordic and mid-latitude countries, the application of *Downing's* model to France shows that here the spatial distribution of water bodies is rendered inadequately.

To illustrate this, we compare the distribution map of small bodies of water in France based on *Down-*

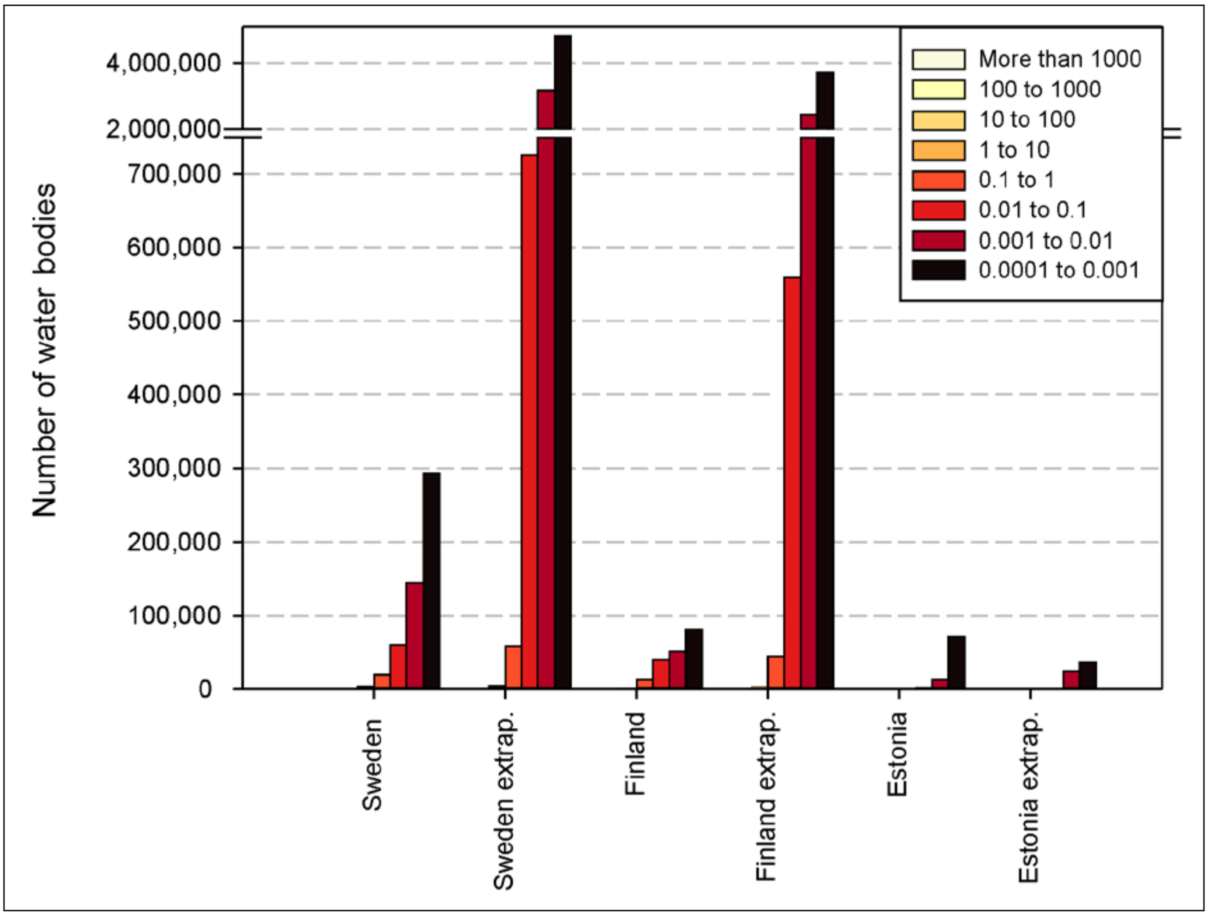

Fig. 8 The French model applied to Sweden, Finland and Estonia

ing's model (*Oertli* and *Frossard* 2013) with the map of water bodies which is derived from field reality (at 98.6 %, *Bartout* and *Touchart* 2013) (*Fig. 7*).

Figure 7 highlights location errors and inaccuracies of data which occur when we apply a model that is based on previously glaciated regions containing primarily natural lakes. The areas with the lowest modeled densities of bodies of water correspond in reality to areas with the highest density of water bodies. Conversely, the areas with high modeled densities of ~~bodies of water~~ are mostly indicated in the areas that in reality do not have bodies of water. The exceptions are the Brenne and Sologne regions which are globally known for their ponds.

Our results show that when we take into consideration small bodies of water, the Swedish model does not perform either in Nordic countries (where it is intended to be representative) or in a state with different limnic characteristics. These findings suggest that the Swedish model cannot be meaningfully used for transfer and extrapolation.

When applying the French limnic model to the three Nordic countries (*Fig. 8*), we have to consider the high increase of water body numbers for size ranges 0.1 to 1 km^2 and 0.01 to 0.1 km^2. They constitute thresholds for which the extrapolation has been performed. After application of these steps, the estimated total numbers for Sweden and Finland increase dramatically. The findings suggest almost 8 million bodies of water in Sweden and 6 million in Finland. These numbers are 16 to 30 times higher than the numbers actually inventoried. On the other hand, the total number of water bodies in Estonia estimated by the French model reaches only 60 % of local reality. This is due to the great difference in connections between the two last classes (*1.5 in France compared to *5.5 in Estonia).

Testing of the model for the lakes count developed in France and the model developed in Sweden suggests that the distribution criterion for the glaciated regions cannot be extrapolated to non-glaciated regions with artificial reservoirs. This means that these examples show incoherencies generated by a "global to local" approach.

4. Discussion

Limnological research suffers from a lack of reliable inventories. The inventories based on *Wetzel's* theory (1990) describe well the distribution of water bodies in Nordic countries and are of great importance for understanding the surface waters in this region. However, as our results indicate, such models are not easily applicable to other geographical regions. Differences in the modeled estimates based on *Wetzel* (1990) and the real counts of water bodies in countries like France and Estonia suggest that a global modeling for estimating lake counts should not be based solely on one region.

Therefore limnological inventories do not depend on a "unique model" which was imported from exact sciences, while its usefulness decreases for geographical and planning problems. Limnological geography takes into consideration both space and time in the centre of its approach and its thinking, and organizes its demonstration depending on upscaling and interlocked scales (*Touchart* 2002, *Touchart* et al. 2014).

If the changes of scale are not taken into consideration, the explanatory factors are selected arbitrarily. Admittedly, questions of scale and differentiated distribution of ~~bodies of water~~ were addressed by *Lehner* and *Döll's* (2004) studies based on remote sensing (*Fig. 2*). But *Downing's* analysis (2006, 2009, 2010), based on only one climatic entry, completely distorts the understanding of global estimates of water bodies. In reality, artificial ponds are located where there is a deficit of water (in order to store water), contrary to what is claimed in *Downing's* maps where artificial ponds are located in regions with a great quantity of water (for filling the ponds), a moist climate and high precipitation and run-off.

The Swedish model built by *Hakanson* and *Peters* (1995) cannot be considered as the only Nordic model. As the Estonian case study shows, these studies need to be considered within their geographical context. That is why the Estonian analysis is useful to illustrate the issues related to inventories of bodies of water. Prior to 2014, the available inventory for Estonia (Estonian Lakes Inventory 2006) was based on exhaustive information about large bodies of water (natural and artificial) and on isolated areas of knowledge for the smallest ones. This complete inventory identified around 2,800 waterbodies. Applying the Swedish model to Estonia means that the official Estonian count improves significantly (*3). Similar results apply also to Finland where fieldwork has been technically much more advanced. However, the improvements in the Estonian inventory (*30) are derived from the technical adaptation to researched objects, i.e. the smallest bodies of water. The same methodological approach has guided French studies where the new inventory (*Bartout* and *Touchart* 2013) contains 15 times more of ~~bodies of water~~ than the previous inventory (BD Carthage in *Banas* 2011). These bodies of water really exist on the ground; that is why their counting is required for improving the reliability of estimates.

The technical contribution has to be adapted to local context, financial resources and tool pertinence. In this way, after studying the French case and some databases in other countries in the European Union, different levels (ranges) of margins of error appear in the data processing: Corine Land Cover (1/100.000) counts less than 0.001 % of the bodies of water, BD Carthage I.G.N (1/50.000) 3 to 4 %, GoogleMap-GoogleEarth 30 to 38 %, Maps (1/25.000) 55 to 70 %, aerophotos with automatic processing (BD Topo I.G.N) 70 to 76 %, satellite imagery 10 m (Spot 5) 71 %, satellite imagery 1 m (Spot 6) 98 %, aerophotos with manual processing 98 % (*Bartout* 2012, *Bartout* and *Touchart* 2013, *Bartout* 2015). It is possible to predict the margin of error based on scale, type of technique and type of data treatment.

These steps allow a reduction in the margin of error by the adoption of a geographical approach suited to size diversity, origins and type of water bodies.

If we apply this logic to Nordic countries in the EU, then "the reference model" for inventorying bodies of water would be the Estonian approach, as it was presented earlier. This approach would significantly modify Swedish and Finnish inventories and it would tackle the recurrent underestimation of small bodies of water (less than 10 ha) and especially the smallest ones (less than 0.1 ha). Multiplying factors of *3.07, *2.42 and *2.03 for the last surface ranges would become *5.74, *6.42 and *5.55. This approach yields the following estimates: more than 4.8 million of bodies of water covering more than 100 m^2 in Sweden, and more than 3.25 million bodies of water in Finland.

Although these three countries have similar climatic conditions, their geographical context is somewhat different (environment, size, history). Therefore, we do not want to affirm that these total numbers correspond to reality; however we want to highlight the potential ranges of errors in the current total estimates which are essentially caused by ignoring the smallest bodies of water.

5. Conclusion

A geographical approach to estimating the number of water bodies must combine limnological knowledge and measures of spatial distribution. Our method based on proof by contradiction and reduction to the absurd shows that one universal relationship is unable to provide reliable global or regional estimates of water bodies since local conditions differ greatly from one region to another and cannot be adequately offset by each other. We show that the widely used idea of *Pareto* (1897) concerning the distribution of lake area by lake size classes is not sufficient for achieving reliable global estimates of ~~bodies of water~~ that would take into account all different types of water bodies.

The current scientific paradigm in limnology, which favours one representative model for different territories, is not able to produce exact global information. Similarly, the water body counts based only on the study of formerly glaciated areas (Russia, Scandinavia, Canada and USA) can provide information only for these regions: local or even regional extrapolations from these data alone are not sufficient for building a global model.

Our study suggests that in order to know the approximate number of water bodies on Earth, it is necessary to aggregate and summarize local work while using appropriate classification and methodologies. Indeed, on a technical level, both mathematical extrapolation and remote sensing approaches enhance the knowledge of geographical distribution and the number of ~~bodies of water~~. However, while the total area of bodies of water is important for a comprehensive study of the water cycle and interactions between water, soil and atmosphere, the number raises more questions about amenities and river continuity (or breaks in continuity).

Automated remote sensing alone cannot solve the problem of accurate estimation of the total number of ~~bodies of water~~ globally (*Verpoorter* et al. 2014), since the specified reliability limit (0.2 ha) is above the median surface of bodies of water, both in Estonia and in France. Cross-checking of the results obtained using several methods with those from fieldwork will improve the census and provide more realistic data than those obtained from remote sensing. Although this approach is time-consuming, it has the advantage of preventing the production of fictional numbers which bear little resemblance to concrete reality concerning the usually overlooked small and artificial bodies of water.

This study shows that the application of the total estimates of water bodies to the limnic density is not successful and can result in huge margins of error. However, we also emphasize that all extrapolations are questionable. Our approach suggests that instead of aiming to achieve very exact figures it is more useful to provide reliable ranges of estimate. The progression from the global to the local scale does not work very well. The top-down progression from the local to the global (or continental) scale requires the definition of many regional equations and a large amount of fieldwork: each geographical region must be described by a specific equation.

Then, collected data reliability must be checked. In this paper we have checked data from three Nordic countries (Estonia, Finland and Sweden) and a Central European country (France), but so far studies of data from the southern countries of the European Union are lacking. In addition, we have processed and smoothed data from the public OpenStreetMap database and improved them by using available scientific databases from inventories (*Bartout* 2015). This work shows that the estimated total number of water bodies of more than $100\,m^2$ on a European Union scale (nearly 4.5 million km^2 of surface area) is 3.5 million. This number is significantly higher than that of the 7.000 bodies of water, which is the estimate of "water masses / ~~water~~" officially agreed upon by European water agencies. However, our estimate is distinctly lower than the possible result if the Estonian model is applied to Denmark, Latvia, Lithuania, Sweden, Finland, even Germany and Poland. Based on these findings we estimate that future field studies on a local and continental scale will significantly increase the total number of known bodies of water. On a world scale, this may result in about one hundred million bodies of water with an area of more than $100\ m^2$; however, a range of billions seems impossible[2].

As it is the aim of societies to manage their bodies of water more efficiently, it is necessary to better understand the diversity of these bodies of water, not only large, natural and old, but also small, artificial and recent. This typological study has to be put in perspective with the internal and external (river continuum, fluvial, hydroclimatic balance, economy, sociology, politics) relationships of ~~bodies of water,~~ For many features, it seems to us that the progression must be from the local to the global scale and must take into account time scales and dynamic evolution.

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Notes

[1] The question of water volume will not be discussed in this paper.

[2] Probably between 200 and 400 million bodies of water if we apply GLOWABO logic (117 million, *Verpoorter* et al. 2014) with an accuracy of 0.2 ha and the difference with reality in Estonia and France, where median sizes are smaller than this area (respectively 0.02 ha in Estonia and 0.09 ha in France).

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